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Technical Report 267

CONTROLLED PERIMETER BLASTING IN COLD REGIONS

Malcolm Mellor

October 1975

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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The general principles of pre-split blasting and smooth blasting are described, and practical procedures that have been developed for work in common rocks are reviewed systematically. The topics covered include shothole spacing, charge weight per unit length of shothole, decoupling ratio, adjustments for explosive type and rock type, and weight of explosive per unit face area. Relevant properties of frozen rocks, frozen soils, and ice are compared with those of common unfrozen rocks, and appropriate adjustment of blast design is discussed. Interim relationships for the design of controlled perimeter blasting in frozen soils and massive ice are put forward, recognizing that additional experimentation is required. Special problems in controlled blasting of ice are discussed. These include effects of wet →

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20. Abstract (cont'd)

holes, delayed removal of burden, and submerged burden. Special attention is given to the cutting of ice islands and icebergs. An Appendix describes an operation in which the face of the ice wharf at McMurdo Sound was trimmed by pre-split blasting.

PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work was done under U.S. Navy reimbursable funds and under DA Project 4A762710AT32 (*Research for Engineer Applications of Nuclear and Non-Nuclear Explosives in Theaters of Operations*), Task 03 (*Explosive Effects in a Winter Environment*).

Preparation of the report was prompted by work carried out by the author at McMurdo Sound, Antarctica, during Deepfreeze '75. This project, described here in an appendix, was sponsored by Commander Thomas W. Kirkpatrick, U.S. Coast Guard, Ship Operations Officer of the Naval Support Force, Antarctica, and the work was performed by U.S. Navy drilling and blasting crews under the able direction of Chief Equipment Officer William L. Wright, U.S. Navy. Technical reviews of the report were provided by North Smith and Paul V. Sellmann of USA CRREL.

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Malcolm Mellor

INTRODUCTION

Traditional rock blasting leaves the finished surface broken and rough, as might be expected after violent destruction by explosives. However, relatively smooth surfaces, with no overbreak, can be produced by various controlled blasting techniques. All involve the drilling of a line of parallel holes at the limit of the excavation, and the loading of these holes with light column charges. Ideally, the charges should be decoupled so that the stress wave is strongly attenuated by the time it enters the rock, thus driving cracks between the holes without much shattering of the adjacent rock. The finish line can be shot before the material to be excavated is blasted (unrelieved blast), or the finish line can be shot as the final stage in sequential removal of material to a free face (relieved blast). For the unrelieved case, the applicable technique is usually known as pre-splitting or pre-shearing, while for the relieved case the technique is most commonly referred to as cushion blasting in aboveground work, and smooth blasting, smoothwall blasting, or perimeter blasting in underground work. There is also a technique known as line drilling, which involves perforation of the perimeter with tightly spaced unloaded holes (2 to 4 hole diameter spacing), but this is virtually mechanical cutting of the finished surface.

In 1974 a problem developed with the ice wharf at McMurdo Sound, Antarctica, and it became necessary to cut a straight vertical face in thick ice to facilitate an important ship loading operation. No suitable cutting machines were available, and controlled blasting seemed the most practical solution, although such techniques had not previously been tried in ice, and ice was known to be somewhat anomalous in its response to explosives. The McMurdo job had a number of complicating factors that precluded simple application of established practices, and the exigencies of the situation ruled out systematic experimentation. Nevertheless, the work provided some practical experience, and the associated design study gave some insight into the general problem of controlled blasting in ice.

This report attempts to provide systematic guidelines for controlled blasting of cold regions ground materials, i.e. frozen rocks, frozen soils, and massive ice. The first step is to make a brief but orderly review of established practices for controlled blasting of common hard rocks, thus producing rationalized data summaries from available recommendations. The second step is to deduce reasonable blast designs for cold regions materials by drawing upon known properties and limited practical experience in order to modify hard rock procedures. Finally, ways of coping with special practical problems in ice are suggested.

GENERAL PRINCIPLES OF CONTROLLED PERIMETER BLASTING

Both pre-splitting and smooth blasting procedures are intended to produce a cleanly defined finished surface that has not been seriously damaged by the explosive. This end is achieved by drilling parallel holes which define the finished surface, and by propagating cracks to link the holes. The holes are used both as line sources of explosively generated pressure and as stress concentrators in the resulting nonisotropic stress field. Damage to the

rock that remains in the finished surface is avoided by decoupling the charges, so that the stress wave has been attenuated by a suitable amplitude by the time it reaches the rock surrounding the shothole.

Pre-splitting, or pre-shearing, is used mainly in surface work. The pre-splitting holes are shot ahead of the main excavation blast, either by means of delays or by a completely separate firing. The rock is completely confined during the pre-splitting shot. The cracking produced along the pre-split line protects the back wall from stress wave damage during the subsequent excavation blast. To achieve the required interaction between shotholes, all pre-splitting charges should be fired simultaneously (within the practical limits imposed by detonator quality control). However, if ground vibration is a problem, short delays can be used without too much loss of quality.

Smooth blasting, in which the innermost row of shotholes is loaded lightly to avoid damaging the finished surface, is practiced in both underground work and aboveground excavation. The burden (i.e., the distance from the shothole line to the free face) has to exceed the shothole spacing within the row if there is to be direct crack propagation between the holes, without cracking and venting to the free face. A burden/spacing ratio of 0.8 is widely accepted as a good working rule. As in pre-split blasting, simultaneous firing of all holes in the row gives best results.

In the interest of drilling economy, it is obviously desirable to space the shotholes as widely as possible, but there are limitations. One limitation is set by the required quality of surface finish, since unevenness is related to hole spacing and hole diameter (for hole spacing of 2 to 4 ft, the average surface roughness is about 1/10 of the hole spacing, or approximately equal to the hole diameter). Another limitation arises because hole spacing and hole diameter have to be approximately proportional in order to maintain the geometric similitude that controls interaction and crack propagation. This means that drill size eventually has to increase, and also that the amount of explosive has to increase in order to maintain the shothole pressure and the required stress level in the rock.

CONTROLLED BLASTING PRACTICE IN COMMON ROCKS

Although pre-splitting and smooth blasting have been studied experimentally (e.g. Langefors and Kihlstrom 1963, Bauer 1968, Kutter and Fairhurst 1968, Atchison et al. 1964), loading procedures tend to be determined from full-scale tests, and there is still an element of art in general field practice. A number of books offer practical guidance on charge weight per unit length for various shothole diameters and spacings (e.g. DuPont deNemours and Company 1969, Canadian Industries, Ltd. 1973, Langefors and Kihlstrom 1963, Gustafsson 1973), but there are no hard and fast design rules that lay down charge concentrations and hole dimensions for various rock types. To make the most of the available recommendations, a systematic summary will be made, and an attempt will be made to develop general relationships.

Hole spacing

In Figures 1 and 2, various recommendations on hole diameter D as a function of hole spacing L have been plotted for pre-splitting and smooth blasting respectively. There is a clear linear relation between D and L in both cases.

For pre-splitting, L/D is mainly in the range 8 to 11, and for simplicity we can take L/D = 10 as a representative value. For relieved smooth blasting, the range of L/D is from 13 to 16, and L/D = 15 can be taken as a representative value.

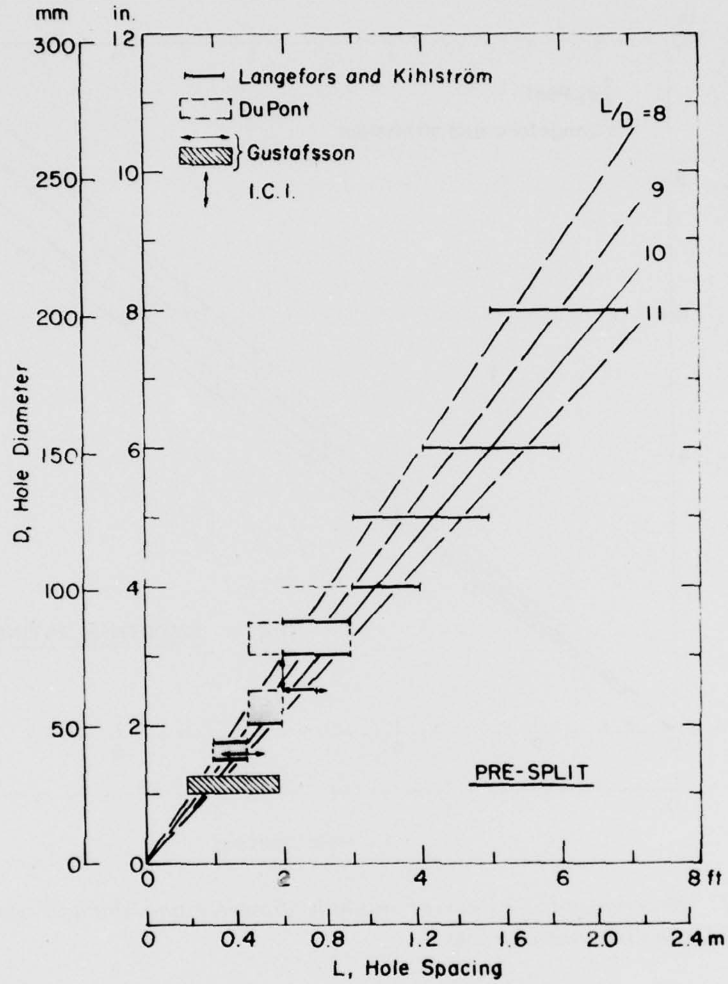


Figure 1. Recommended values of shothole diameter and shothole spacing for pre-split blasting in common rocks.

With $L/D \geq 10$, the holes are effectively independent as stress raisers. In a uniaxial stress field, or in a nonisotropic biaxial stress field, each hole gives an initial stress concentration factor of 3 at the boundary points cut by a diameter that is normal to the major principal stress. The stress is tensile at these points when the major principal stress is tensile. The stress concentration factor decays asymptotically to unity with radial distance, and there is no significant effect beyond about $2D$ from the center of the hole. However, with a row of charges fired simultaneously, stress waves and gas pressure ought to produce a stress field favoring crack propagation along the common centerline of the shotholes. With $L/D = 10$, any centerline crack only has to extend for a total distance of $4D$ to $5D$ before it is in a position to link up with a crack propagating in the opposite direction.

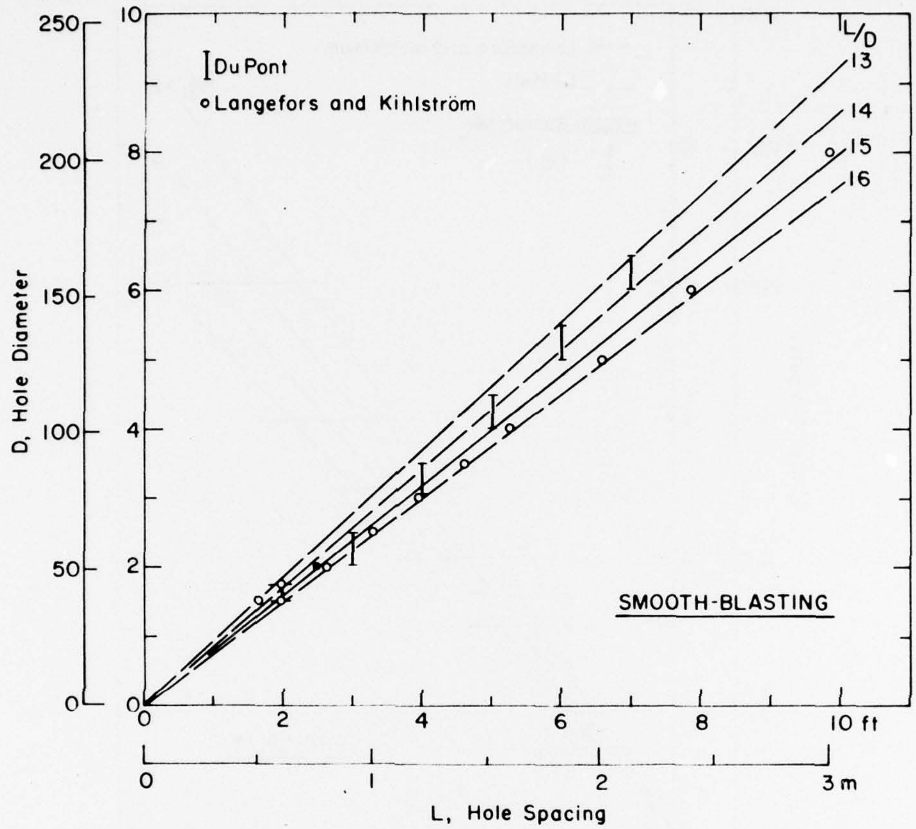


Figure 2. Recommended values of shothole diameter and shothole spacing for smooth blasting in common rocks.

Charge weight per unit length

Recommended values of charge weight per unit length of shothole w are plotted against shothole diameter D in Figure 3. The recommendations are essentially the same for both pre-splitting and relieved smooth blasting.

On the logarithmic plot of Figure 3 there is a fairly clear linear correlation between recommended values of w and D, and from a purely empirical standpoint a simple relation of the form $w = kd^2$ is indicated. The midrange data are well represented by

$$w = 0.037\,D^2 \quad \text{lb/ft} \tag{1a}$$

where D is in inches, and by

$$w = 8.5 \times 10^{-5} D^2 \quad \text{kg/m} \tag{1b}$$

where D is in millimeters.

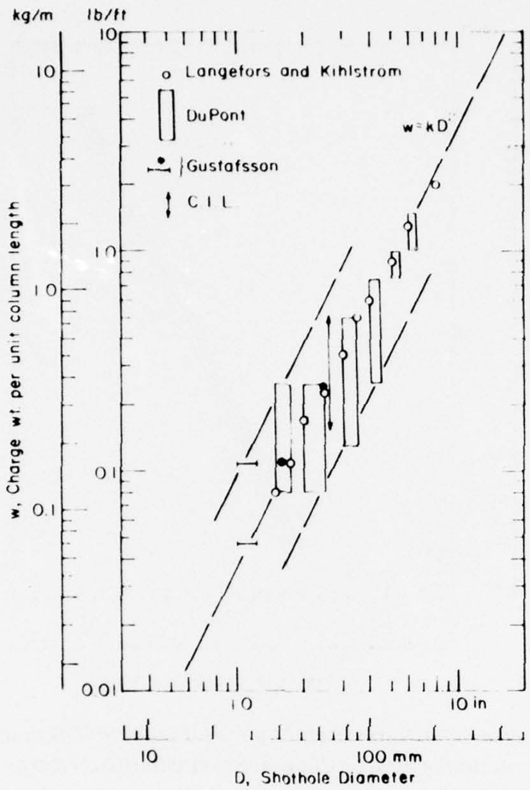


Figure 3. Recommended values of charge weight per unit column length plotted against shothole diameter (for existing rock-blasting practice).

Decoupling ratio

If the charge is in the form of a continuous cylindrical column, as is desirable, then the charge weight per unit length of shothole can be expressed in terms of the charge diameter d and the specific gravity of the explosive G_s:

$$w = 0.340\, G_s d^2 \quad \text{lb/ft} \tag{2a}$$

where d is in inches, and

$$w = 7.85 \times 10^{-4}\, G_s d^2 \quad \text{kg/m} \tag{2b}$$

where d is in millimeters. The relationship is shown graphically in Figure 4.

Combining eq 1 and 2, we can obtain a relation between D and d:

$$D/d = 3.04(G_s)^{\frac{1}{2}}. \tag{3}$$

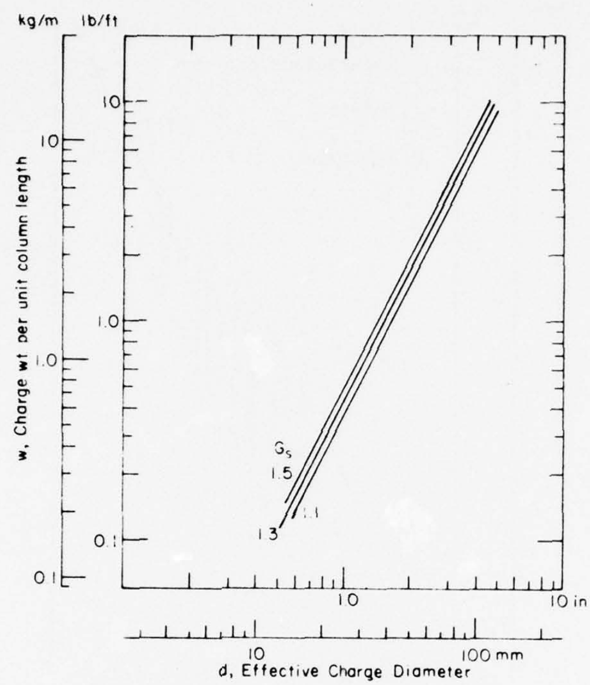


Figure 4. Charge weight per unit column length as a function of charge diameter for cylindrical charges of various densities.

With a typical solid explosive of specific gravity 1.3, this gives a value of D/d = 3.5.

It might be noted that d is the diameter of the explosive itself; since the measured diameter of a charge usually includes the thickness of the packaging shell, the measured value of D/d would be somewhat smaller than 3.5.

The ratio D/d is often called the *decoupling ratio*. The inverse, expressed as a percentage, is sometimes taken as a measure of the effectiveness of geometric coupling (as distinct from impedance coupling). Since L/D seems to have been well established on the basis of experience for both pre-splitting and smooth blasting, the key to blast design is the determination of an appropriate value for the decoupling ratio D/d.

If the charge is not a continuous column, then an effective decoupling ratio can be defined by the square root of unstemmed hole volume divided by explosive volume.

The decoupling ratio defined above is a simple and rational blasting parameter as long as the annulus between the charge and hole wall remains unstemmed. However, it becomes more difficult to analyze the decoupling process when the shothole is fully stemmed with material of unspecified porosity, as it often is in heavily fractured formations.

Adjustment of decoupling ratio for explosive type

In field practice, it is not usual to take systematic account of explosive type in determining the required decoupling ratio, but in principle there ought to be a relationship. One effect of explosive density is shown in eq 3, but this is not of much practical significance, since the likely variation in $(G_s)^{\frac{1}{2}}$ is small. A more important factor is the detonation pressure of the explosive.

Detonation pressure p_d is not normally given in explosives data sheets, but it can be calculated adequately from the detonation velocity U and the specific gravity G_s. There are a variety of approximate equations of the form

$$p_d = U^2 f(G_s) \tag{4}$$

in which the density function $f(G_s)$ is not likely to produce more than about 20% total variation over the whole range of ordinary explosives. The detonation velocity, however, could vary from about 3.5 to 6 km/s, giving a potential variation of p_d by a factor of 3.

If the objective is to adjust the decoupling ratio so as to maintain constant stress level at the wall of the borehole when the explosive type is varied, then one theoretical possibility is to base the adjustment on adiabatic expansion of the gaseous detonation products, as suggested by Atchison and Duvall (1962) and Atchison et al. (1964). For long column charges assumed to detonate instantaneously in holes that are sealed but not side-stemmed, this leads to

$$D/d \propto (p_d)^{1/2\gamma} \tag{5}$$

or

$$D/d \propto U^{1/\gamma} \tag{6}$$

in which γ, the ratio of specific heats for the explosion gases, can be taken as 1.2 for typical explosives (Atchison et al. 1964, Brown 1956).

Ignoring the small effect of the density function in eq 4, adjustment of the decoupling ratio for explosive type could thus be based on eq 3 and eq 6. For example, if $D/d = 3.5$ has been found to be a good working value for midrange explosives represented by $G_s = 1.3$ and $U = 5$ km/s, then the decoupling ratio could be adjusted for a different type of explosive from

$$D/d = 3.5\,(G_s/1.3)^{1/2}\,(U/5)^{0.83}. \tag{7}$$

This assumes that the detonation behavior of the explosive is not changing with the decoupling ratio, as might conceivably happen at very small decoupling ratios with charges that are close to critical diameter.

Adjustment of hole spacing and decoupling ratio for rock type

Rock strength is usually ignored in ordinary controlled blasting work, but in principle it should affect at least the decoupling requirements, and for present purposes it can hardly be overlooked.

Assuming that the rock behaves elastically beyond the immediate vicinity of the hole wall, the required spacing/diameter ratio L/D ought to be insensitive to rock type as far as stress concentration and crack guidance effects go. However, the stress level required to fracture the rock at any given scaled distance ought to be proportional to the fracture strength. If the charge is well decoupled, to the extent that typical close-range energy dissipating effects are substantially eliminated, then stress wave attenuation in the seismic zone ought to be insensitive to material type for short propagation distances of the order of $4D$. Thus the peak stress level reached at any given point in the rock should be approximately proportional to the effective borehole pressure (see standard elasticity solutions for a pressurized hole), and for a given type of explosive this should be determined largely by the decoupling ratio D/d.

If the appropriate measure of rock strength is S, then the decoupling ratio for unstemmed hole can be adjusted, on the basis of gas expansion considerations, in the same way as the adjustment was made for explosive type:

$$D/d \propto S^{-1/2\gamma}. \tag{8}$$

Ideally, S should represent failure in the complicated multiaxial dynamic stress field that actually prevails during the explosive event, but in fact it is necessary to use a simpler measure of strength. Uniaxial tensile strength is commonly regarded as characterizing resistance to blasting damage, while uniaxial compressive strength is often the only known strength property for particular rocks.

If the ratio of compressive strength to tensile strength is assumed to be constant for common rocks (it actually varies by about a factor of 2), the rock strength adjustment can be made on the basis of the uniaxial compressive strength S_c. The common range for S_c might be taken as 0.5 to 2.0 kbar (7000 to 29,000 lbf/in.^{2}), and the midrange value of the decoupling ratio, $D/d = 3.5$, might be taken as representative for $S_c = 1$ kbar (15,000 lbf/in.^{2}). The corresponding range for D/d would then be from 4.7 to 2.6 on the basis of the adjustment relation:

$$D/d = 3.5/S_c^{0.42} \tag{9}$$

where S_c is in kilobars. However, when the ratio of compressive strength to tensile strength is anomalous, as it is for ice and some frozen soils, then eq 9 could be misleading.

Weight of explosive per unit face area

Loading recommendations for pre-splitting (pre-shearing) are sometimes given in terms of the weight of explosive per unit face area, a quantity that is referred to as the "pre-shear factor." However, recommendations given this way can be quite confusing, as they tend to ignore the fact that the pre-shear factor has to vary systematically with the size and spacing of shotholes.

The pre-shear factor F_{ps} is given approximately by

$$F_{ps} = w/L \tag{10}$$

when collar distance is neglected. If the ratio L/D is held constant, so as to maintain geometric similitude in the shothole array, then it can be seen from eq 1 that the pre-shear factor has to be proportional to the shothole spacing L or to the shothole diameter D:

$$F_{ps} = w/L = \text{constant} \times D^2/L = \text{constant} \times D = \text{constant} \times L. \tag{11}$$

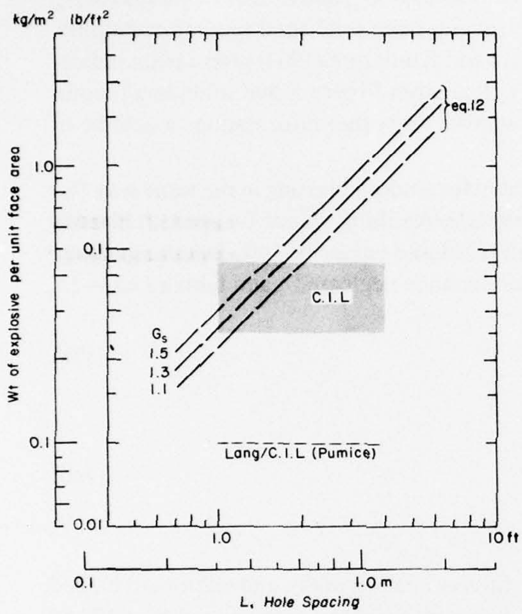
If D/L is taken as 10 and D/d is taken as 3.5, then

$$F_{ps} = 0.040\, G_s\, L \qquad \text{lb/ft}^2 \tag{12a}$$

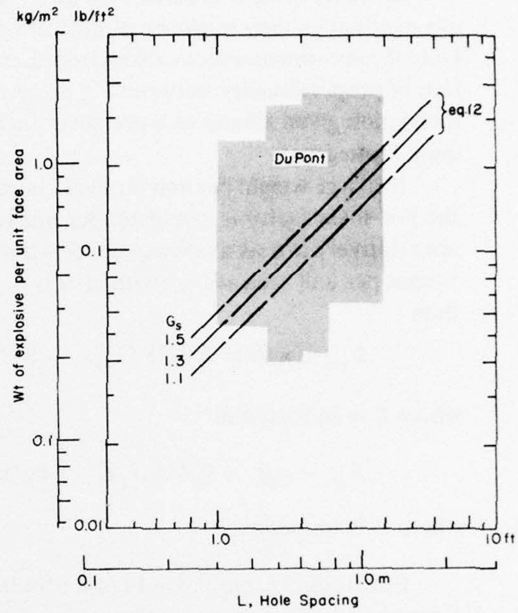
where L is in feet, and

$$F_{ps} = 0.641\, G_s\, L \qquad \text{kg/m}^2 \tag{12b}$$

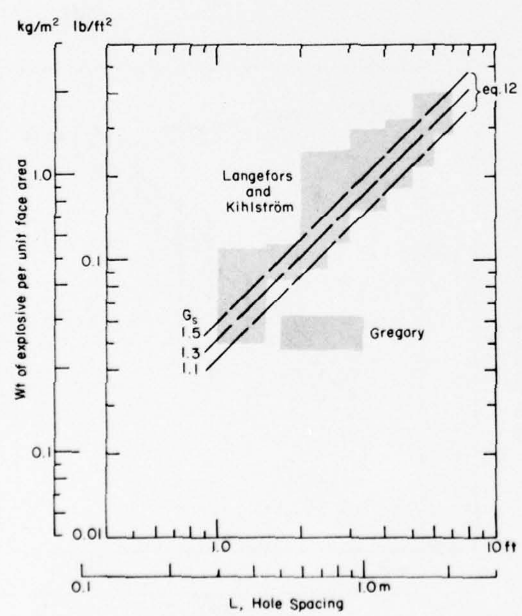
where L is in meters.



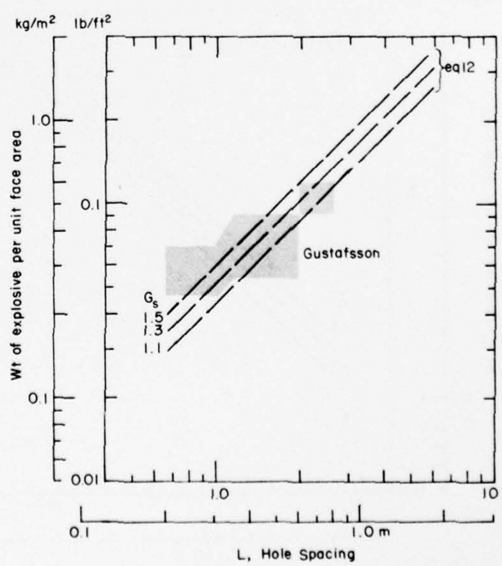
a. Following C.I.L. 1973.



b. Following DuPont 1969.



c. Following Gregory 1973 and Langefors and Kihlstrom 1963



d. Following Gustafsson 1973.

Figure 5. Weight of explosive per unit face area plotted against shothole spacing following the recommendations of various authorities for pre-split blasting in common rocks.

In Figure 5, eq 12 is plotted for three different values of G_s, and ranges of values for F_{ps} are overlaid as they might be plotted after abstracting from published recommendations. Only the recommendations taken from Langefors and Kihlstrom (1963) give a plain indication of proportionality between F_{ps} and L. It is clear from Figure 5 that a loading recommendation given simply as a pre-shear factor, without any other information, would be of quite limited use.

If charge weight per unit face area is calculated for smooth blasting in the same way that the pre-shear factor is calculated for pre-splitting, the resulting values for smooth blasting are relatively low as a consequence of the relatively large values of L/D. Denoting charge weight per unit area as F_{sm} (with effects of collar distance neglected), and taking $L/D = 15$, then

$$F_{sm} = w/L = 0.0178\, G_s\, L \qquad \text{lb/ft}^2 \tag{13a}$$

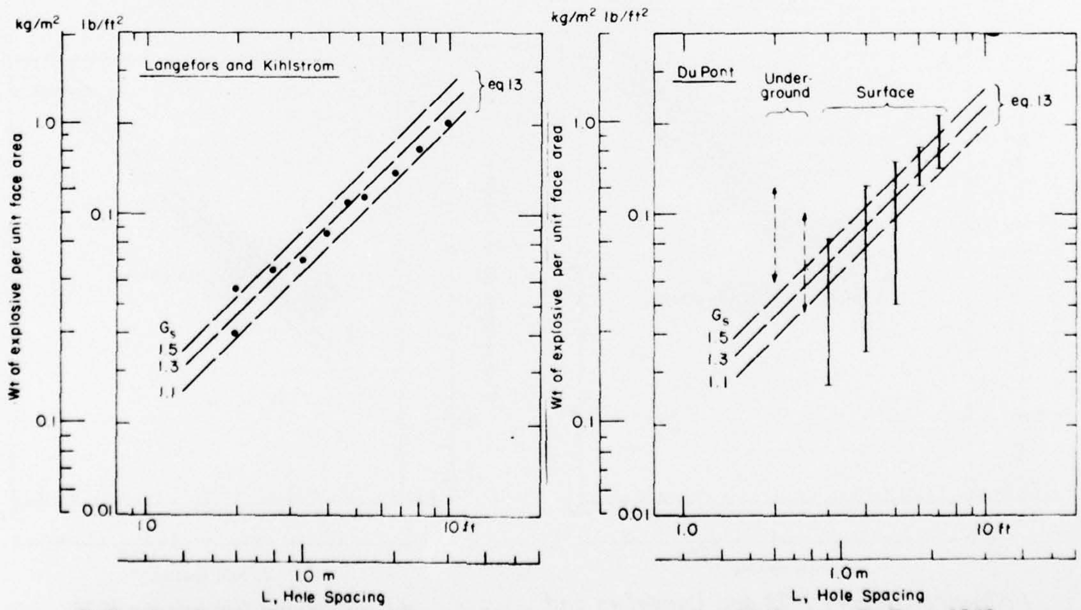
where L is in feet, and

$$F_{sm} = w/L = 0.285\, G_s\, L \qquad \text{kg/m}^2 \tag{13b}$$

where L is in meters.

Equation 13 is plotted in Figure 6 for three different values of G_s, and values developed from published recommendations are overlaid. As can be seen from comparison of eq 12 and eq 13, the charge weight per unit face area in smooth blasting is typically about half that used in pre-splitting:

$$F_{ps}/F_{sm} = 2.25. \tag{14}$$



a. Following Langefors and Kihlstrom 1963. *b. Following DuPont 1969.*

Figure 6. Weight of explosive per unit face area plotted against shothole spacing following recommendations for smooth blasting.

PRE-SPLITTING AND SMOOTH BLASTING IN FROZEN ROCKS

The pore water in typical rocks freezes progressively as the temperature is lowered from the freezing point of bulk water, and for each rock type there is a characteristic relationship between unfrozen water content and temperature that depends largely on the specific surface area of pores and internal microcracks. For "air-dry" rocks, values of strength and moduli do not increase very much under the influence of low temperatures, but in water-saturated rocks there are dramatic increases in strength and moduli at low temperatures. The changes are most strongly marked in high-porosity rocks, which can be transformed from relatively weak materials with appreciable compressibility into very strong rocks (as strong as unfrozen granite) that have low volumetric compressibility. Even a sound granite, with porosity less than 1%, can increase in strength by about 30% when its pore water freezes.

These changes, while significant for general explosive excavation, may not be judged to be of critical concern in controlled perimeter blasting, since they are within the usual range of variability for unfrozen rocks. However, it is probably advisable to make a systematic check on proposed loading in order to ensure that changes in explosive properties and rock properties do not combine to degrade the results. A possible procedure can be illustrated by a simple numerical example.

Example 1. Design a pre-split blast that will produce a clean vertical face in a frozen sandstone that has a uniaxial compressive strength of 25,000 lbf/in.^{2} (ignoring collar distance in this example).

1. Taking into account desired shothole spacing for drilling economy and acceptable surface roughness, choose the shothole diameter D which will have its actual value set by available sizes of drill bits. Suppose the aim is to have a shothole spacing of about 3 ft (0.91 m): with an L/D ratio of 10 the indicated value of D would be 3.6 in. (91 mm). The closest size of an available drill bit might be an even 4 in. (102 mm), and this would be accepted as the final value of D.

2. Take an L/D ratio and calculate hole spacing L. $L/D = 8$ would be very conservative, while $L/D = 11$ would be at the optimistic end of the range according to current pre-splitting practice. If $L/D = 10$ is accepted, then the hole spacing becomes 40 in. (1.02 m).

3. Check on available explosives. With a hole diameter D of 4 in. (102 mm) and a decoupling ratio of 3.5, the required charge diameter for a continuous column is 1.14 in. (29 mm). Suppose the only available explosive that can be coupled or threaded easily into a continuous column has a nominal diameter of 1.25 in. (32 mm), and an effective charge diameter (excluding thickness of packaging shell), 1.15 in. (29 mm). If this size of cartridge is used, the decoupling ratio is almost exactly 3.5, and the loading is in accordance with the midrange value suggested by eq 1. Suppose that the detonation velocity of the available explosive is fairly high, say 6 km/s; this will increase the pressure level felt by the wall of the shothole above the midrange value.

4. Check whether the tentative loading figure is reasonable for the strength of the rock. Take 1 kbar (15,000 lbf/in.^{2}) as the reference strength and 4.75 km/s (16,000 ft/s) as the reference detonation velocity for midrange loading. Assume that the decoupling ratio should be proportional to detonation velocity and inversely proportional to rock strength raised to the power 2.4, and estimate a target value for the ideal decoupling ratio. This is $(3.5) \times (6/4.75) \times (15{,}000/25{,}000)^{1/2.4} = 3.6$. Thus the proposed loading should be satisfactory.

RELEVANT PROPERTIES OF FROZEN SOILS AND MASSIVE ICE

Under slow loading, ice and fine-grained frozen soils are much more ductile than common rocks, but at very high loading rates they deform elastically and fail by brittle

fracture, so that qualitatively their response to explosives is very similar to that of ordinary rocks. However, in quantitative terms the behavior of ice is significantly different from that of common rocks, and it is not nearly so easy to blast as its low strength and low density might suggest. By extension, similar though less marked anomalies are found with ice-bonded soils.

Ice is much weaker than typical hard rock. Its uniaxial compressive strength is an order of magnitude lower than typical values for sound rock, and about 5% of the value for a strong granite. Ice has a dynamic Young's modulus that is about 20% of the value for a granite or a sound sedimentary rock, and its bulk density is about 1/3 that of typical rocks. However, while the tensile strength of ice is less than representative values for fairly weak sedimentary rocks, and about 15% of the value for a good granite, the ratio of tensile strength to compressive strength is high in ice.

The ratio of uniaxial compressive strength to uniaxial tensile strength for ice appears to be less than 5, and possibly as low as 3, whereas for common rocks it is almost always greater than 8 and usually greater than 10. This ratio has been used by Hino (1956) to define a "blastability coefficient," and the implication of this definition is that ice has low "blastability." Ice was used as a model material in pioneer experimental studies of blasting with low explosives (Daw and Daw 1898), but the resulting predictive equation was found to be somewhat unreliable when applied to ordinary rocks. In a recent reinvestigation of this work (Clark and Saluja 1964, Saluja 1968), the discrepancy was atrributed partly to the small difference between compressive and tensile strengths for ice at 0°C.

For crater blasting in ordinary rocks, explosive yield (volume or mass of rock broken per unit weight of explosive) has been successfully correlated with uniaxial compressive strength. This procedure, which is in line with the well-established practice of normalizing "process specific energy" with respect to compressive strength, fails completely when cratering data for ice are included. Values of scaled volumes for optimum craters in typical hard rocks overlap the corresponding values for glacier ice; midrange values for rock and ice might differ by a factor of 2, whereas the corresponding values of compressive strength differ by an order of magnitude.

In experimental bench blasting with a somewhat unreliable explosive, ice appeared to give about the same values of yield and load factor as would be expected in bench blasting of ordinary hard rocks.

In well-coupled blasts of the cratering and benching type, the unexpectedly high resistance of ice to explosive loading may be due partly to the very high compressibility of ice under extreme pressure, which seems to lead to strong attenuation at relatively long distances from the charge. In decoupled blasts, it may be that the nature of the failure criterion for ice is the main consideration.

Frozen soils have textural similarities to certain rocks. For example, ice-cemented silts and sands are similar to siltstone and sandstone respectively, while frozen gravel is similar to conglomerate or to concrete. With high loading rates and low temperatures, frozen soils are comparable in compressive strength to the weaker sedimentary rocks, and their elastic moduli are comparable to those for dense rocks. However, the compressive strength values that are usually reported for frozen soils are low — about 500 to 5000 lbf/in.^{2} (0.035 to 0.35 kbar).

While failure criteria for frozen soils have not been investigated systematically, the indications are that the ratio of uniaxial compressive strength to uniaxial tensile strength is well below typical values for common rocks, and may be quite similar to the values found for ice itself. Some recent tests at CRREL indicate a ratio of about 3 for frozen silt tested at high rates of loading, with temperatures near 0°C.

Crater blasting experiments in frozen silt and frozen gravel show that explosive yields lie within the typical range for common rocks. Optimum depth crater blasts give 25 to 50 ft^3/lb in frozen silt, and 15 to 30 ft^3/lb in frozen mixtures of gravel and silt. In other words, the apparently low strength of frozen soil does not result in easy blasting.

PRE-SPLITTING AND SMOOTH BLASTING IN FROZEN SOILS AND MASSIVE ICE

As fa[illegible], smooth blasting to a free face has not been tried in ice so far. Many years ago, experimental blasting to set dimensions and perimeter geometry was undertaken on several occasions during underground excavation work in Greenland, but the results were not very satisfactory, mainly because of overfragmentation and shattering of the finished surface (which had serious consequences in openings of more than 12 ft span). The only known attempt at pre-splitting in ice is the recent work described in the Appendix to this report. This job had a number of complicating features, but it did provide some practical insight into the problems of working with ice.

In frozen soils, there do not seem to have been any attempts to use controlled blasting methods.

From the foregoing notes on material properties, it is clear that attempts to adjust loading procedures solely on the basis of generally accepted strength values for ice and frozen ground would be unwise. However, since strength is the only property that can be used quantitatively, some consideration has to be given to this. It seems best to adjust loading by comparing tensile strength for rock and frozen material, either directly or by comparing compressive strengths and using a factor given by the ratio of blastability coefficients for rock and frozen material. In both cases, the result indicates an adjustment of the decoupling ratio from the 3.5 adopted for rocks to a value of about 6 for ice and fine-grained frozen soils.

On the basis of limited experience, a decoupling ratio of 6 is felt to be too high for ice and frozen soils. This can perhaps be rationalized in the following way. In common rocks, 3.5 is usually less than the critical decoupling ratio; i.e. there is a transitional damage zone between the hole wall and the seismic zone (in which the strain wave is elastic). Within this transitional zone, attenuation depends on the properties of the material, and the indications are that ice and frozen soils give relatively strong attenuation at close range. Thus, for comparable action in rock and frozen materials, an appropriate loading adjustment may be needed.

Taking everything into consideration, it is suggested that a decoupling ratio of 5 should be adopted for both ice and frozen soil when an explosive of midrange velocity is used. With this ratio the required charge weight per unit length w becomes

$$w = 0.340\, G_s\, d^2 = 0.0136\, G_s\, D^2 \quad \text{lb/ft} \tag{15a}$$

where d and D are in inches, and

$$w = 7.85 \times 10^{-4}\, G_s\, d^2 = 3.14 \times 10^{-5}\, G_s\, D^2 \quad \text{kg/m} \tag{15b}$$

where d and D are in millimeters.

With a chosen value of L/D for either pre-splitting or smooth blasting, the charge weight per unit length can be expressed in alternative form as a function of L by substituting D in the above relations.

With $D/d = 5$ and $L/D = 10$ for pre-splitting in ice and frozen soils, the pre-shear factor F_{ps} is

$$F_{ps} = w/L = 0.0196\, G_s\, L \quad \text{lb/ft}^2 \tag{16a}$$

where L is in feet, and

$$F_{ps} = 0.314\, G_s\, L \quad \text{kg/m}^2 \tag{16b}$$

where L is in meters.

With $D/d = 5$ and $L/D = 15$ for smooth blasting in ice and frozen soils, the charge weight per unit face area F_{sm} is

$$F_{sm} = w/L = 8.70 \times 10^{-3}\, G_s\, L \quad \text{lb/ft}^2 \tag{17a}$$

where L is in feet, and

$$F_{sm} = 0.140\, G_s\, L \quad \text{kg/m}^2 \tag{17b}$$

where L is in meters.

These suggested loadings are shown graphically in Figures 7-9.

Since practical blast design usually involves compromises, it may be useful to give a simple example.

Example II. Repeat Example I, substituting for the frozen rock of that example a frozen gravel of 5000 lbf/in.^{2} compressive strength.

Following the procedure of steps 1 and 2 in Example I, establish $L = 40$ in. (1.02 m), $D = 4$ in. (102 mm). Check on available explosive, recognizing that a decoup;lng ratio greater than 3.5 will probably be needed. Suppose that the only available small diameter explosive which can be linked easily into continuous column charges has a nominal diameter of 0.875 in. (22 mm), an effective diameter of 0.82 in. (21 mm), and a detonation velocity of 4 km/s. Ignoring the exact value of ground strength, and adjusting the suggested value of the decoupling ratio only on the basis of detonation velocity, the target value for the decoupling ratio is $5 \times (4/4.75) = 4.2$. The actual value with the available explosive is 4.9, which is probably acceptable if the holes are stemmed.

There is one other important aspect in which ice and frozen soils differ from frozen rocks. Fine cracks are capable of healing, especially when there is vapor diffusion or water infiltration, and for this reason pre-split blasts should be followed up without undue delay, removing the burden before the pre-split surface can refreeze.

So far, the subject of collar distance has not been broached. In normal pre-splitting and smooth blasting, an unloaded collar is left at the upper end of the borehole to allow for a plug of stemming and to avoid ragged breakage of the lip from cratering effects. An optimum collar distance has not been determined experimentally for ice and frozen ground, but it appears that a reasonable estimate can be made by regarding the explosive located within 10

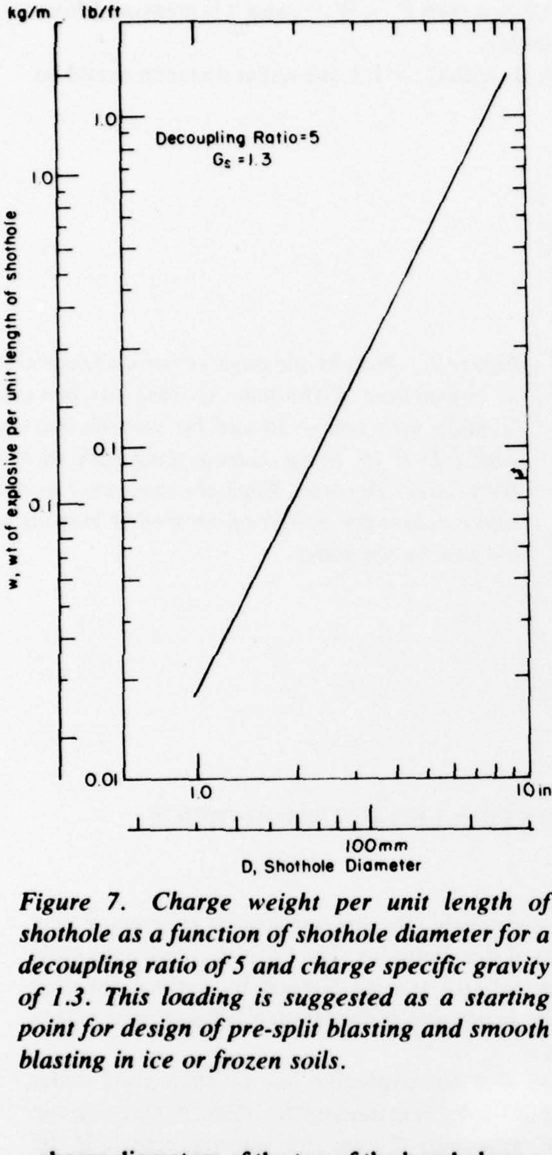


Figure 7. Charge weight per unit length of shothole as a function of shothole diameter for a decoupling ratio of 5 and charge specific gravity of 1.3. This loading is suggested as a starting point for design of pre-split blasting and smooth blasting in ice or frozen soils.

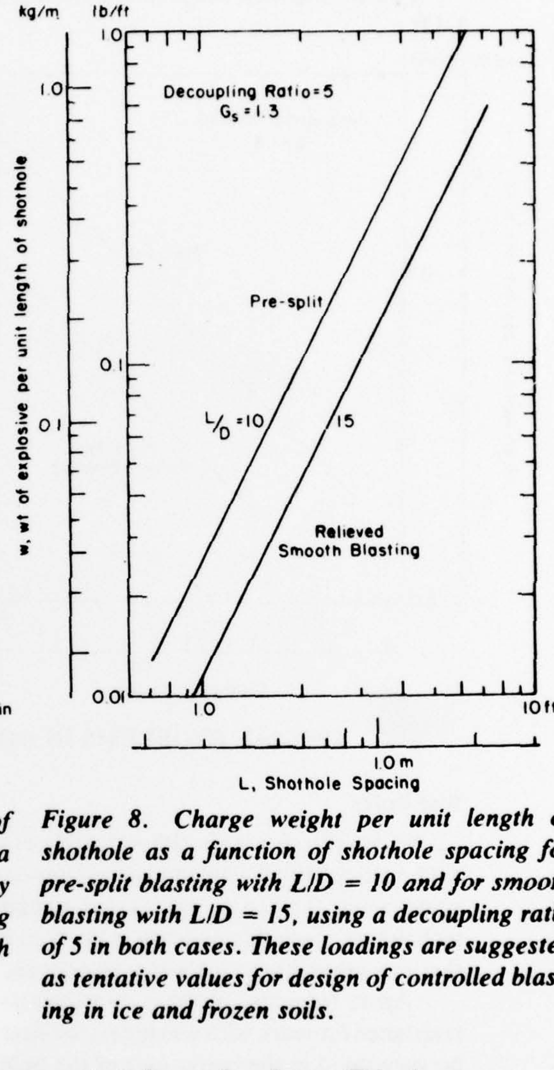


Figure 8. Charge weight per unit length of shothole as a function of shothole spacing for pre-split blasting with L/D = 10 and for smooth blasting with L/D = 15, using a decoupling ratio of 5 in both cases. These loadings are suggested as tentative values for design of controlled blasting in ice and frozen soils.

charge diameters of the top of the borehole as a concentrated cratering charge. This charge weight W_T is

$$W_T = 0.283\, G_s\, d^3 \quad \text{lb} \tag{18a}$$

where d is in inches, and

$$W_T = 7.85 \times 10^{-6}\, G_s\, d^3 \quad \text{kg} \tag{18b}$$

where d is in millimeters. Collar distance is taken as the critical depth for a cratering charge of this size. Scaled critical depth Z_c can be taken as 5 ft/lb$^{1/3}$ for ice, 3 ft/lb$^{1/3}$ for frozen silt,

and 2.7 ft/lb$^{1/3}$ for frozen gravel. Collar distance is then $Z_c \times W_T{}^{1/3}$, and it is measured from the top of the charge to the lip of the shothole.

For the situation described in Example II, with $G_s = 1.3$, the collar distance would be 3.4 ft.

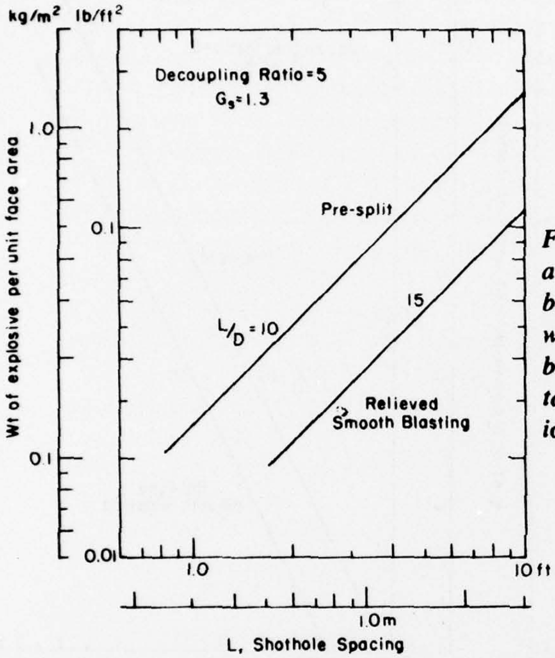


Figure 9. Weight of explosive per unit face area as a function of shothole spacing for pre-split blasting with L/D = 10 and for smooth blasting with L/D = 15, using a decoupling ratio of 5 in both cases. These loadings are suggested as tentative values for design of controlled blasting in ice and frozen soils.

SPECIAL PROBLEMS IN CONTROLLED BLASTING OF ICE

Wet holes

When massive ice is either floating or grounded in the sea, in lakes, or in rivers, it may not be practically feasible to keep water out of the shotholes. The problem is perhaps most acute when the ice to be blasted is high salinity sea ice formed by surface flooding techniques, since this material is likely to be permeable at the relatively high temperatures that can prevail near ice/water interfaces.

Apart from the obvious consideration that the explosive has to have good water resistance for work with wet holes, the first difficulty is in loading the holes. Refreezing can be very rapid in the upper part of the hole, especially if some drill cuttings remain in the water. A simple solution is to load each hole immediately after drilling, taking appropriate safety precautions when the explosive is being handled in close proximity to the drilling equipment.

A more bothersome question is whether or not the effects of decoupling can be obtained when the space between the charge and the hole wall is completely filled with water. Clearly, there is perfect geometric coupling in a water-filled hole, and the characteristic impedance coupling appears to be such that the small stress loss across the explosive/water interface is roughly balanced by stress amplification at the water/ice interface.* However, the water does provide strong close-range attenuation, and its response to the explosive loading is truly hydrodynamic in the immediate vicinity of the charge, with no shear resistance and no crack initiation. Thus there is no real difference in principle between an

* In the acoustic impedance-matching formula, an initial *shock* velocity of 5.5 km/s is used for water, rather than the elastic wave velocity of 1.5 km/s.

air-filled annulus and a water-filled annulus, but for equal stress levels at the hole wall the decoupling ratio D/d ought to be higher for the water-filled hole. Without information on the close-range attenuation relations for end-initiated explosive columns in air and in water, the adjustment of the decoupling ratio cannot be estimated analytically. On the basis of experience, it appears that a decoupling ratio of 5 is insufficient to avoid damage to the ice surrounding the hole wall, but for many purposes the damage resulting from this type of loading would be quite acceptable. Until the ideal decoupling ratio for water-filled holes can be established experimentally, it might be prudent to plan on using a decoupling ratio of 6, making some provision for further adjustment in the field. Results can be improved by holding down the shothole spacing, and possibly by using low velocity explosives.

In sections of the hole that refreeze, the charge obviously is not decoupled, except by the inherent compressibility of ice. If the pre-split shot can be fired without undue delay, it is quite likely that only a short length of each shothole will be refrozen, especially if some allowance for refreezing has been made in the initial D/d ratio. Under these circumstances there may not be much loss of quality, but if quality is of great concern it may be justifiable to retard freezeback by adding some kind of antifreeze to the upper part of each hole — possibly DFA (diesel fuel-arctic) dispersed in the ice slush.

Actually, a high degree of smoothness is not likely to be of much concern with ice, since ablation will probably remove the worst of the roughness after a relatively short time.

When controlled blasting is performed with water-filled holes, perhaps water stemming (or drilling mud) could be used to economize on explosive for routine work in tight rock formations. With the newly available heavy detonating cord (400 grain/ft), it should be easy to provide light column charges that might suffice for pre-splitting or smooth blasting in water-filled holes.

Delayed removal of burden

It has already been mentioned that delay in removal of burden after pre-splitting in ice may result in partial healing of the crack, and an actual instance of this is recorded in the Appendix. This can create difficulties where natural effects, such as gravity or free flotation, are relied upon to remove the burden, but the consequences are not likely to be serious where the burden is removed by bench blasting back to the pre-split line. The worst situation for refreezing of a pre-split line is one in which fresh water infiltrates a crack in cold ice; healing by vapor diffusion in cold, dry ice, however, should not be too troublesome.

Adjustment for submerged burden

In underwater blasting, loading is usually adjusted to compensate for the confining effect of water pressure. Practical recommendations by Gustafsson (1973) include an addition to the weight of explosive of 1% per meter of water depth. In controlled blasting where no "heave" or "throw" is required, adjustment is probably unnecessary for work in shallow water, say less than 20 m deep. In smooth blasting it may be possible to reduce the burden when water provides confinement, but under these circumstances it might be advisable to use the loading for a pre-split operation, i.e. reducing L/D to approximately 10. If very deep cuts were to be attempted, say in cutting an iceberg, then it might be necessary to take account of the effect of bulk stress on the fracture strength of the ice.

Cutting ice islands and icebergs

Considerable attention has been given to the destruction of ice islands and icebergs by explosives, both for protection of shipping and for protection of offshore structures. Bench

blasting and cratering have been studied, as well as the rather futile expedients of conventional bombing and shelling. Without going into details of these studies, it appears from comparative calculations that pre-split blasting might also be worth consideration as a technique for destruction or reduction, provided that shothole drilling could be accomplished quickly and efficiently. However, a more obvious application for controlled blasting would be in precise cutting. In the case of arctic ice islands this might be for docking purposes, while in the case of Antarctic icebergs there is potential interest in forming shapes suitable for towing, and in carving bergs up for processing into potable water.

In making long cuts, there would be an incentive to use large diameter shotholes so as to minimize the number of holes, and thereby the number of set-ups for the drill. It might also be desirable to allow the shotholes to fill with water, trading minor deterioration of surface finish for the insurance of slight overshooting. To get an idea of the effort involved, consider the cutting of a 120-ft-square, 60-ft-thick, ice island fragment of the kind that drifts into the offshore oilfields of the western Arctic. With 6-in.-diam shotholes and an L/D ratio of 10, shothole spacing would be 5 ft. For a 120-ft-long cut, 24 holes would be needed. Loading in accordance with eq 15 and Figure 7, the charge weight would be about 0.636 lb/ft, or 35 lb per hole for 60-ft deep holes with a 5-ft collar. For the complete cut, 840 lb of explosive would be required.

If the whole island were to be cut into 20-ft-wide vertical slices, 5 parallel cuts would be needed, i.e. 120 holes and 4200 lb of explosive. Each additional cross-cut, chopping through all of the slices at right angles, would call for 18 more holes and 630 lb more explosive. For comparison, if the same island were to be completely destroyed by crater blasting, the job might be accomplished with 4 to 9 chambered shotholes and 2 to 3 tons of explosive (taking advantage of all free boundaries). Total destruction by sequential bench blasting might call for about 63 shotholes and 10 tons of explosive.

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APPENDIX A: TRIMMING THE ICE WHARF AT MCMURDO SOUND

After many years of difficulties with ship berthing at McMurdo Sound, including total failure of a conventionally constructed quay, a wharf of thick floating ice was constructed by repetitive surface flooding. At the beginning of the first operating season, the face of the newly made ice wharf had a heavy fringe of adhering sea ice, which resisted various attempts at removal. Finally, in trying to scrape the sea ice from the face of the wharf with the bow of an icebreaker, the wharf was rammed and broken into a number of separate pieces. The main pieces were tied together with cables, but the berthing face was left irregular after the loss of some smaller fragments. In this condition the wharf functioned adequately during the first operating season, but for the second season the face had to be straightened so as to permit loading of a heavy radioactive pressure vessel from a condemned nuclear power plant (see Fig. A1).

It was decided that the trimming work would be done by controlled perimeter blasting, although controlled blasting had not previously been attempted in ice. In the original planning it was assumed that the annual sea ice would be removed from the bay prior to blasting, and the burden was expected to range from 0 to about 25 ft. The procedure was expected to be a mixture of pre-splitting and smooth blasting, depending on the local burden, with the complication that the face (or bench) would be submerged for most of its depth. Under these circumstances the burden would have been free to float clear after the blast. However, weather conditions were unfavorable for ice clearing by the breakers, and the blasting was actually carried out with heavy sea ice confining the face of the wharf.

The average thickness of the wharf along the cut line was 22 ft, and the total length of the wharf cut line was approximately 470 ft. The annual sea ice in the bay was 8 ft thick, and the annual sea ice adhering to the sides of the wharf was 10 to 14 ft thick. The cracks that had been driven through the wharf the previous year had refrozen to a depth of approximately 8 ft. The whole surface of the ice wharf was covered with a layer of gravel several inches thick, and one end of the cut line passed through a dump of dunnage that was bonded together by ice.

The blasting work had to be carried out with explosives that were already available at McMurdo Sound. The only feasible choice was 60% gelatin dynamite in standard 1¼ × 8-in. cartridges. The dynamite sticks were threaded onto reinforced Primacord to give the required weight per unit length of shothole.

Shotholes were drilled with a track-mounted percussive drill (Worthington 2275), using air circulation from a 650 cfm compressor. The largest available bit had a diameter of 3.5 in., and this size was used throughout. With this size of hole, normal rock practice would indicate hole spacing of about 3 ft for pre-splitting and about 4½ ft for smooth blasting to a free face. There were some problems with the drilling operation (excessive breakage of connecting collars, bit loss and shortage of spares, rapid refreezing, miserable working conditions), and a compromise shothole arrangement was developed after one set of holes, covering a 150-ft section, had been lost by loading delay. With heavy sea ice packed against the face, the operation became essentially pre-splitting along the whole cut line, and so full depth holes (22 ft) were drilled at 4-ft centers, with interspersed 10-ft deep holes also at 4-ft centers. The 10-ft holes, which acted as extra guide holes over the depth range of the annual sea ice, could be drilled rapidly with a single drill steel, whereas the addition and removal of an extra steel for the deeper holes involved three coupling and three uncoupling actions. Both the full depth and the 10-ft holes filled with water to sea level, since the ice of the wharf was permeable. Cuttings and ice slush were cleared from each hole as far as possible by flushing air through for 1 or 2 min at the end of the drilling run.

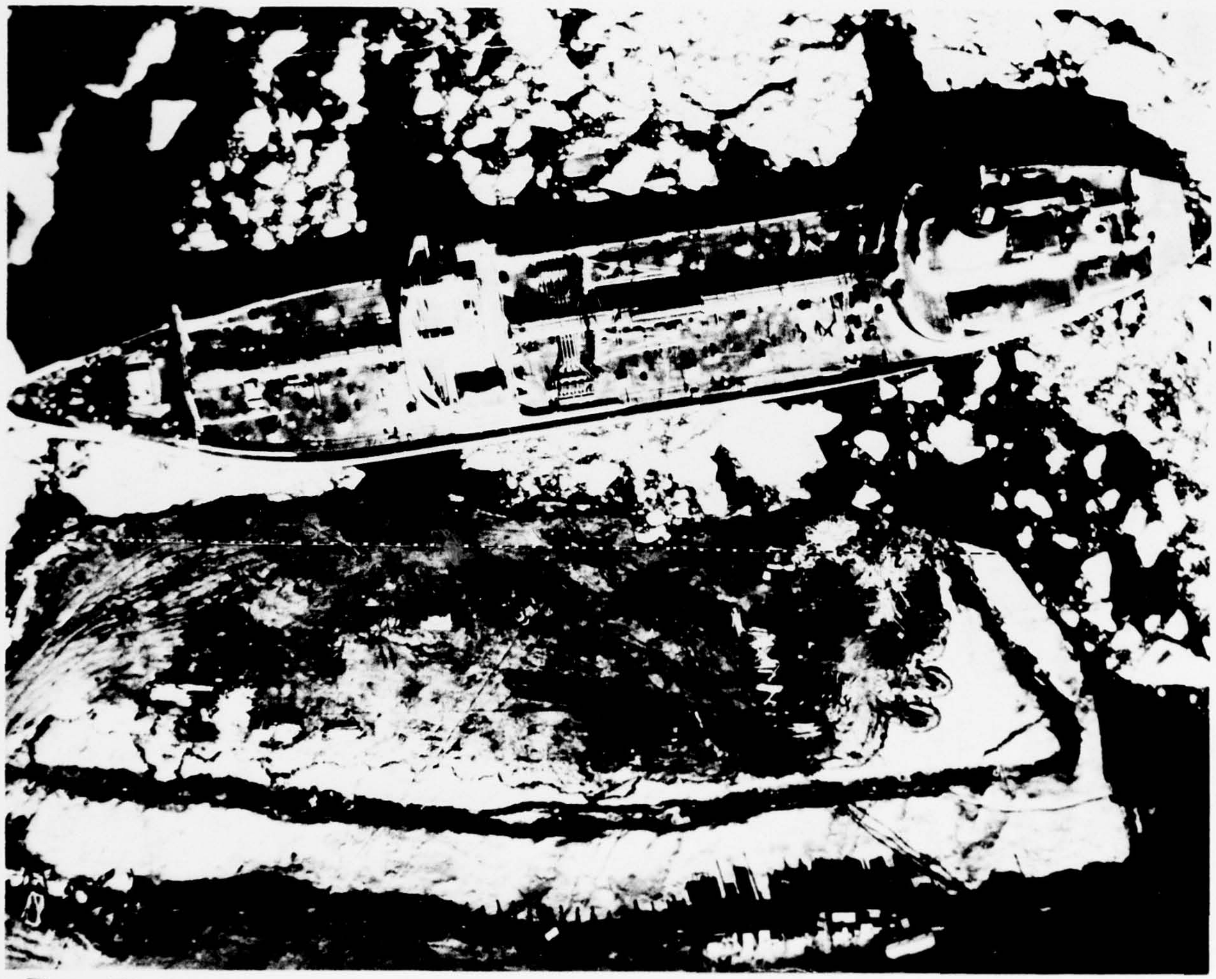

Figure A1. *Aerial view of the ice wharf at McMurdo Sound in February 1974, showing the irregular face and the cut line blasted in January 1975. The tanker in the picture, the USNS Maumee, is 620 ft long.*

The cut line was extended into the adjacent sea ice by drilling shotholes with an electrically powered hand flight-auger.

According to eq 15 and Figure 7, a 3.5-in.-diam *open* hole in ice might require about 0.22 lb/ft of explosive. The loading actually used was 0.25 lb/ft, which was obtained by setting one ½-lb cartridge every 2 ft along the detonating cord (16-in. spacing between ends of 8-in. cartridges). This made some allowance for the unloaded collar, which was set at 3 ft for the first blast and 4 ft for subsequent blasts (the top cartridge behaved as a cratering charge). A heavy sinker was attached to the bottom end of each Primacord downline, and an attempt was made to clear the shothole immediately before loading by ramming with a pole.

The unloaded collar of each shothole was stemmed with gravel, which tended to bridge when immersed and mixed with the ice slush that accumulated in the upper part of each hole. The detonating cord downlines were then connected to a surface trunkline for minimum-delay firing. Careful attention was given to downline connections to avoid inadvertent cutoff.

The first blast covered a 160-ft section known as Section B. It appeared to produce a clean break along the cut line, but no shear displacement was evident. The 3-ft collar gave too much surface heave, but there were no signs of significant backbreak.

At this stage, operations ceased because the icebreakers were unable to reach the harbor area. Drilling and loading on the remaining section (Section A) resumed two days later, and this work was completed three days after the initial blast was fired. Because the icebreakers were still held up, firing on this section was delayed for a further two days.

When the main 300-ft section of the cut line (Section A) was eventually fired, there was an unexplained trunkline cutoff about halfway along the line, and in the section that did detonate there were seven branchline misfires. The remaining trunkline was doubled up, and fresh Primacord tails were taped to the misfired downlines, providing as much overlap as possible after chipping-out part of the collars. After a second firing there were still a total of eight misfired branchlines, and since the accessible tails were completely destroyed, these charges had to be abandoned. From case markings, it was deduced that the explosives supplied for this project had been shipped to Antarctica 20 years earlier.

Shortly after completion of this blast, the icebreaker *Burton Island* moved into the bay and broke up the annual sea ice. During this disturbance, the ice outboard of the cut line on Section A separated neatly, leaving a clean vertical face over a depth of 22 ft. The separated ice rolled onto its side, displaying a section through the shotholes (and revealing a fine collection of unexploded charges). The icebreaker then tied up alongside Section A.

The following day, several holes were drilled along the Section B cut line, which had been shot 6 days earlier. The split had apparently refrozen to a depth of 5 ft. The holes were loaded and fired to "shake-up" the split, but the ice did not separate. *Burton Island* then moved in through the adjacent ice floes and, with great precision, placed her bow on the end of the Section B cut line. As she applied thrust and downpressure, the ice separated neatly along the cut line.

This completed the job of restoring a straight and vertical face to the ice wharf, and shortly afterwards the USNS *Pvt. John R. Towle* berthed and began working cargo (Fig. A2).

In these blasts, all holes were water-filled; the top charge (and possibly one other charge) in each hole was completely coupled by refreezing, and the decoupling ratio in the upper section of each hole was probably reduced by refreezing. The pre-split line was undoubtedly overshot, or at least it would have been if all the charges had detonated. Nevertheless, the final result was quite acceptable — there was no serious backbreak and

Figure A2. USNS Pvt. John R. Towle tied up against the trimmed face of the McMurdo ice wharf after the blasting operation of January 1975.

the old cracks in the wharf were not reopened by blasting (although one was rebroken by ship forces). The tendency for overloading was fully recognized at the time of the blasts, but it was hoped that multiple cracking along the pre-split face would minimize freezeback problems (as it probably did). The other hope, which proved vain, was that a heavy shot might provide a positive displacement of the burden.

The major difficulty in accomplishing the work was timing. In retrospect, it appears that the job could have been done with less fuss by quickly drilling, loading, and firing after the harbor had been cleared of annual sea ice. However, to do this without risk of serious delay, it would have been necessary to have on hand two drills (with adequate spares), enough qualified operators to run the drills for two shifts a day, proper pre-splitting explosive (of recent vintage), and a good loading crew.